

Carbon footprint of cropping systems with grain legumes and cover crops: A case-study in SW France



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ABSTRACT

Agriculture contributes to a significant proportion of global emissions of greenhouse gases (GHG) but can also participate in climate change mitigation. The introduction of legumes in crop rotations reduces the dependence on N fertilizers and may mitigate the carbon (C) footprint of cropping systems. The aim of this study was to quantify the C footprint of six low-input arable cropping systems resulting from the combination of three levels of grain legumes introduction in a 3-yr rotation (GLO: no grain legumes, GL1: 1 grain legume, GL2: 2 grain legumes) and the use of cover crops (CC) or bare fallow (BF) between cash crops, covering two rotation cycles (6 years). The approach considered external emissions, on-site emissions and soil organic carbon (SOC) stock changes, and prioritized (i) field observations and (ii) simulation of non-measured variables with the STICS model, rather than default emission factors. As expected, fertilizers accounted for 80–90% of external emissions, being reduced by 50% and 102% with grain legumes introduction in GL1-BF and GL2-BF, compared to the cereal-based rotation (GLO-BF). Cover crops management increased machinery emissions by 24–35% compared to BF. Soil nitrous oxide (N₂O) emissions were low, ranging between 205 and 333 kg CO₂ eq. ha⁻¹ yr⁻¹ in GL1-BF and GLO-BF, respectively. Nitrate leaching represented the indirect emission of 11.6 to 27.2 kg CO₂ eq. ha⁻¹ yr⁻¹ in the BF treatments and 8.2 to 10.7 kg CO₂ eq. ha⁻¹ yr⁻¹ in the CC treatments. Indirect emissions due to ammonia volatilization ranged between 8.4 and 41.8 kg CO₂ eq. ha⁻¹ yr⁻¹. The introduction of grain legumes strongly influenced SOC changes and, consequently, the C footprint. In the BF systems, grain legumes introduction in the rotations led to a significant increase in the C footprint, because of higher SOC losses. Contrarily, the use of cover crops mitigated SOC losses, and lowered the C footprint. These results indicated the need of CC when increasing the number of grain legumes in cereal-based rotations. Despite the multiple known benefits of introducing grain legumes in cropping systems our research highlights the need to consider soil organic carbon changes in environmental assessments.

1. Introduction

Agricultural production contributes to a significant proportion of global emissions of greenhouse gases (GHG), which contribute to global warming. The emissions related to fertilizer production and application to crops, machinery use, and various soil processes represent the main mechanisms underlying GHG emission to the atmosphere from arable crop production (Gan et al., 2012). In this context, the quantification of the carbon footprint is an appropriate tool to estimate the impact of crop production on climate (Knudsen et al., 2014). The C footprint is defined as “the quantity of GHG expressed in terms of carbon dioxide

equivalents emitted to the atmosphere by an individual, organization, process, product or event from within a specified boundary” (Pandey et al., 2011).

During the last decades, agricultural production in western countries has relied strongly on the application of nitrogen (N) fertilizers. The availability of synthetic N facilitated the specialization of arable cropping systems on the production of cereals, and made European agriculture highly dependent on synthetic fertilizer-N. However, the mismanagement of this fertilizer, e.g. use of excessive rates and/or application at periods of low crop needs, leads to negative environmental impacts. Among other, nitrate pollution of groundwaters,

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Fig. 1. Cropping systems studied in the field experiment. GL0, GL1 and GL2 stand for three-year rotation with 0, 1, and 2 grain legumes. Cash crops (big circles) and cover crops (small circles) are shown. For color version of this figure, the reader is referred to the online version of this article.

atmospheric pollution from ammonia volatilization, and contribution to global warming due to nitrous oxide (N_2O) emissions constitute main environmental risks derived from inadequate N fertilizer management in agriculture (Bouwman et al., 2013). The diversification of cropping systems with the introduction of legumes as cash crops, cover crops or intercrops represents a key strategy to reduce N fertilizer needs at the crop- and rotation scale (e.g. Bedoussac et al., 2015; Plaza-Bonilla et al., 2017b). Crop rotation with legumes also leads to other agronomic and environmental benefits such as a break-crop effect, which encompasses a range of factors that enhance the production of the subsequent crop due to the improvement of growing conditions (Watson et al., 2017). However, to maximize their benefits, the introduction of legumes requires the adaptation of the cropping system (Plaza-Bonilla et al., 2017b; Reckling et al., 2015).

Currently, the environmental assessments of crop production, such as the C footprint face different limitations. Knudsen et al., (2014) stressed the importance of analyzing the full crop rotation when quantifying the C footprint of low-input cropping systems. The statement of Knudsen et al., (2014) was based on the high reliance of low-input systems on nutrient recycling and green manuring, where the different cash and cover crops of a rotation are interlinked. Different authors also highlighted the need to include soil organic carbon (SOC) changes in C footprint assessments, given the impact of crop rotations and management practices on SOC (Gan et al., 2012; Knudsen et al., 2014; Pandey and Agrawal, 2014). In this line, the inclusion of cover crops in cropping systems has been reported as a feasible strategy to increase the amount of soil organic C (Poeplau and Don, 2015), highlighting the need to include SOC changes in environmental assessments (Prechsl et al., 2017). SOC change is a dynamic, equilibrium oriented process, with constant in- and outflows that depend on management and environmental conditions. Inherent to this perception is that a given stock of SOC can only be depleted once; changes in management would always leave the soil carbon and N cycles strive to a new equilibrium. Essential is thereby the time required to arrive at a new equilibrium and how to set up an experimental approach that captures the new equilibrium.

Another aspect of controversy is the use of global default values for estimating soil GHG emissions, given the extreme variability of pedoclimatic conditions and cropping systems in which crop production takes place, which leads to significant uncertainties in the calculation of some processes such as the emission of N_2O from soils. Regarding to this, Barton et al. (2014) pointed out the need to use site-specific field-based measurements to assess greenhouse gases emissions from cropping systems including grain legumes. Consequently, the collection of empirical data and the use of biogeochemical models can help to increase the accuracy of current GHG emissions assessments (Lares-Orozco et al., 2016). The aim of this study was to quantify the impact of introducing grain legumes and cover crops on the C footprint of low-input cropping systems in an area of SW France. We hypothesized that

the diversification of cropping systems with legumes would decrease the C footprint thanks to the savings in synthetic N fertilizer, while the use of cover crops would decrease the C footprint thanks to their positive impact on SOC by increasing the photosynthetic activity versus time according to calendar year. Cover crop residues allow adding C to the soil. The approach considered external emissions and on-site emissions. The impact of the inclusion of soil organic carbon (SOC) stock changes on the C footprint calculation was also assessed, as crop rotations and management practices play a major role on the capacity of soils to store C due to their effects on soil organic C mineralization and crop residues C inputs.

2. Materials and methods

2.1. Experimental design

A field experiment was established in 2003 in the Institut National de la Recherche Agronomique (INRA) in Auzeville (SW France, $43^\circ 31' 42''$ N, $1^\circ 28' 56''$ E), representative of the pedoclimatic conditions of the Garonne valley. The aim of the experiment was the design and assessment of different low-input innovative cropping systems based on the introduction of grain legumes and cover crops. The cropping systems mainly differed in the amount of synthetic N fertilizer required. Over the last three decades, mean annual rainfall, air temperature and potential evapotranspiration were 685 mm, 13.7°C , and 905 mm, respectively. Soil characteristics (0–30 cm depth) were analyzed at the beginning of the experiment: soil texture was clay loam, mean (± 1 standard deviation) pH (H_2O , 1:2.5) was 7.0 ± 0.5 , CEC was $18.1 \pm 3.6 \text{ cmol}^+ \text{ kg}^{-1}$, organic C was $8.7 \pm 1.0 \text{ g kg}^{-1}$ and organic N was $1.1 \pm 0.1 \text{ g kg}^{-1}$.

Six different cropping systems were compared being the result of the combination of three levels of grain legumes introduction in a 3-yr rotation (GL0: no grain legumes, GL1: 1 grain legume, GL2: 2 grain legumes) and the use of cover crops (CC) or bare fallow (BF) between cash crops (Fig. 1). The GL0 treatment consisted in a sorghum (*Sorghum bicolor* L.) – sunflower (*Helianthus annuus* L.) – durum wheat (*Triticum turgidum* L.) rotation, the GL1 treatment consisted in a sunflower – winter pea (*Pisum sativum* L.) – durum wheat rotation and the GL2 treatment consisted in a soybean (*Glycine max* L.) – spring pea – durum wheat rotation. Durum wheat was a common crop in the three rotations to act as an indicator of the carryover effect of the different cropping systems. Different cover crops were used on each cropping system. In the GL0-CC system cover crops were vetch (*Vicia sativa* L.) and a vetch – oat (*Avena sativa* L.) mixture aimed to increase soil nitrogen availability for subsequent crops and reduce mineral nitrogen applications. In GL1-CC winter pea was accompanied by previous and succeeding mustard (*Sinapis alba* L.) cover crops aimed at reducing nitrate losses, while durum wheat was followed by a vetch-oat mixture to increase soil nitrogen availability. Finally, in GL2-CC mustard was used after spring

pea and durum wheat to reduce nitrate leaching given the higher presence of legumes in the rotation (Fig. 1). The analytical framework is based on the comparison of different cropping systems, each including a rotation with different crops and a management adapted to the specific crops sequence e.g. through individual fertilizer and tillage choices. This approach aims to consider the different adaptations that need to be carried out for an optimum functioning of cropping systems as done usually by farmers: e.g. adapting management practices such as N fertilization, tillage, irrigation, etc. to the sequence of crops and cover crops of the rotation and their impact on soil water, C and N dynamics. The first cropping season is not taken into account in the present study to avoid effects of the previous management on the results. Therefore, two cycles of a 3-year rotation (2005–2007 and 2008–2010) are analyzed. Within each 3-year rotation, each crop was grown every year to account for interannual climatic variability. The experiment was replicated in two contiguous blocks to include variability in soil texture.

2.2. Crop management

Soil management was based on conventional intensive tillage using farmer's machinery as is traditional in the area. A pass of rotary harrow was implemented before sowing. In some years, a pass of moldboard plow was used to control weeds mechanically, to reduce the use of herbicides. A pass of cultipacker was used to ensure good contact between the soil and cover crops seeds. A disk plow was used to incorporate cover crops into the soil. As the experiment aimed at reducing chemical inputs, the destruction of cover crops was always done mechanically when the cover was not destroyed by frost, by the usual soil tillage or by a specific operation such as chopping crop residues before soil plowing, without using herbicide. One or two passes of a camera steering system guiding a cultivator were implemented to control weeds between sorghum and sunflower rows depending on the presence of weeds. Small grain crops were seeded with a commercial seed driller, while a pneumatic row planter was used for sorghum, sunflower and soybean. Average sowing dates of cash crops can be found in Table 1. Different cultivars were used over the duration of the experiment to reduce the susceptibility to pathogens.

Nitrogen fertilization (only for non-legume cash crops) was adapted each year according to the balance-sheet method, considering: (i) requirements of the crop, (ii) residual soil N, and (iii) N mineralization estimated using a predicted mineral N balance (Plaza-Bonilla et al., 2017b). Nitrogen fertilizer was applied with a pneumatic precision applicator splitting the rate in two or three applications (i.e. before

Table 1

Average sowing and harvest dates of cash crops and sowing rate ranges for cash and cover crops used in the experiment. In the vetch-oat crop mixture, values refer to the crop between brackets.

Crop	Sowing date	Harvest date	Seeding rate (seeds m ⁻²)
Durum wheat	November	July (first fortnight)	278–413
Winter pea	December	June (last fortnight)	70–93
Spring pea	February	June (last fortnight)	100–113
Sorghum	end April – beginning May	September (last fortnight)	29–32
Sunflower	April (last fortnight)	September	6.6–6.7
Soybean	May (first week)	end September – beginning October	36–39
(Vetch)-Oat	After cash crop harvest	Not harvested	31–83
Vetch-(Oat)	After cash crop harvest	Not harvested	43–170
Vetch	After cash crop harvest	Not harvested	50–76
Mustard	After cash crop harvest	Not harvested	135–172

Table 2
Nitrogen fertilizer rates applied to the different cash crops in the cropping systems studied (GL0, GL1 and GL2, 3-year rotation with 0, 1 and 2 grain legumes, respectively; BF and CC, bare fallow and cover crops, respectively). Splits of N to durum wheat are shown. Note that no N fertilizer was applied to grain legumes and cover crops.

Rotation	Cash crop	N fertilizer application (kg N ha ⁻¹)													
		Bare fallow (BF)						Cover crop (CC)							
		2005	2006	2007	2008	2009	2010	Mean	2005	2006	2007	2008	2009	2010	Mean
GL0	Durum wheat	132 + 50	99 + 50	100 + 54	101 + 57	42 + 74 + 55	100 + 80	166	88 + 50	99 + 50	100 + 54	101 + 57	42 + 74 + 55	100 + 80	158
	Sorghum	76	76	82	83	112	60	82	76	76	82	83	112	60	82
	Sunflower	56	51	51	62	67	40	55	56	51	51	62	67	40	55
3-yr N applied								303							295
GL1	Durum wheat	66 + 50	50 + 50	50 + 54	40 + 57	106 + 55	60 + 80	120	66 + 50	99 + 50	100 + 54	70 + 57	106 + 55	80 + 80	145
	Sunflower	0	0	0	0	34	0	6	0	0	0	0	34	0	6
	Winter pea	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3-yr N applied								128							151
GL2	Durum wheat	88 + 50	50 + 50	50 + 54	40 + 57	42 + 37 + 55	80 + 50	117	88 + 50	99 + 50	50 + 54	70 + 57	42 + 56 + 55	60 + 50	130
	Soybean	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Spring pea	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3-yr N applied								117							130

sowing, beginning of stem elongation and booting) of ammonium nitrate for durum wheat and one single application of urea before sowing for sunflower and sorghum (Table 2). Depending on the cropping system 3–4 phosphorus (P) applications were carried out during the experimental period as triple superphosphate (45% P_2O_5) before sowing according to soil analysis. Soil potassium levels were enough to satisfy crop needs according to soil analyses. Cash crop protection was performed according to the principles of integrated pest management. In general, one herbicide application was performed to all crops after sowing while, in some cases, other applications were carried out according to the sanitary state of crops. One or two fungicide applications were performed in durum wheat and pea. Sorghum and soybean were irrigated with a hose reel irrigation system during summer because of high demand for plant transpiration and low rainfall. The irrigation water rate was calculated to reach a target of ca. 80% of the maximum evapotranspiration of the crop. The same irrigation rate was applied to the CC and BF systems. Cash crop harvest (Table 1) was carried out with a commercial harvesting machine. A sub-sample was taken to determine grain moisture. The amount of grain C produced on each cropping system was calculated assuming a common grain C concentration of 420 g kg^{-1} whereas grain N was calculated as the product between dry matter grain yield and grain N concentration, quantified by Dumas' method analysis. All crop residues were incorporated into the soil. During the development of the field experiment data regarding crop management practices carried out (i.e. date, type of practice), machinery and/or implements used, 115-hp tractor fuel consumption per ha, and type and rate/dose of inputs were registered.

2.3. Quantification of the carbon footprint

In order to compare the carbon footprint of the different cropping systems, the boundaries were established at field level. External emissions, on-site emissions and SOC stocks changes versus time were considered using the approaches described below. Based on the findings of Jambert et al. (1997) who worked in an arable area of SW France close to the present experiment, methane fluxes were considered negligible, being the maximum emission values reported by the authors of $8.4 \text{ g C-CH}_4 \text{ ha}^{-1} \text{ d}^{-1}$.

External emissions comprised the production and transport of seeds, pesticides, N and P fertilizers and energy needed to pump irrigation water. The calculation involved the product between the amount of each input and its emission factor (EF) (Table 3). In the case of pesticides containing more than one active ingredient (a.i.) the EF was calculated considering the (i) EF for each a.i., (ii) dose of each a.i., and (iii) the sum of a factor ($0.4 \text{ kg Ceq kg a.i.}^{-1}$) to account for the emissions linked to the formulation process (Lal, 2004).

Table 3

Emission factors (EF) for the different inputs used in the cropping systems experiment.

Input type	Description	EF	Source
Fertilizer	Ammonium nitrate	$1.11 \text{ kg Ceq kg}^{-1}$	Ceschia et al. (2010)
	Urea	$1.29 \text{ kg Ceq kg}^{-1}$	
	Triple superphosphate	$0.42 \text{ kg Ceq kg}^{-1}$	
Herbicides	Different active ingredients	Range: $0.41\text{--}5.80 \text{ kg Ceq kg}^{-1} \text{ a.i.}$	Audsley et al. (2009) Lal (2004)
Fungicides	Different active ingredients	Range: $0.55\text{--}1.95 \text{ kg Ceq kg}^{-1} \text{ a.i.}$	Audsley et al. (2009) Gaillard et al. (1997)
Insecticides	Different active ingredients	Range: $1.54\text{--}1.90 \text{ kg Ceq kg}^{-1} \text{ a.i.}$	Audsley et al. (2009)
Irrigation	Energy for pumping water	$0.516 \text{ kg Ceq mm}^{-1}$	Ceschia et al. (2010)
Seeds		$0.04\text{--}0.21 \text{ kg Ceq kg}^{-1}$	ADEME (2011)

Table 4

Farming operations carried out in the field experiment, and associated tools/implements, and fuel consumption.

Farming operation	Tool/Implement	Fuel consumption (L ha^{-1})
Fertilization	Pneumatic spreader 800 L	1.5
Harvest	Medium-sized combine	18
Irrigation	Hose reel irrigation system	–
Mechanical weed control	Cultivator (camera steering system)	5
Pesticides application	Sprayer	2
Residues chopping	Shredder	10
Rolling	Cultipacker	3
Sowing – Small grains	Seed driller	7
Sowing – Coarse grains	Pneumatic row planter	4.5
Tillage – Cultivation	Cultivator	12
Tillage – Harrowing	Disk harrow – 22 disks	10
Tillage – Germinator	Tine harrow	6.5
Tillage – Plowing	Moldboard plow	27
Tillage – Harrowing	Rotary Harrow	13
Tillage – Subsoiling	Subsoiler	17
Tillage – Shallow cultivation	Vibro-cultivator	6

On-site emissions comprised machinery emissions because of fuel consumption, soil N_2O direct emissions, N_2O indirect emissions due to nitrate leaching to groundwater and deposition of ammonia volatilized and carbon dioxide (CO_2) emissions because of urea hydrolysis. To quantify machinery emissions a fuel emission factor of $0.9 \text{ kg Ceq kg}^{-1}$ (Lal, 2004) was multiplied by the amount of fuel consumed by each implement pass on an hectare basis (Table 4). Soil N_2O emissions, nitrate leaching and ammonia volatilization were simulated with the STICS model which was satisfactorily evaluated with a predictive quality of various types of outputs of water, C and N dynamic balances on this site (Plaza-Bonilla et al., 2015). We used model efficiency to measure the agreement between simulated and observed values. This statistical criterion ranges between 1, indicating perfect match between simulated and observed values, and infinite negative value, when observed mean is a better predictor than the model. In this line, model efficiency was 0.64 and 0.37 indicating correct performance for simulating soil water and mineral N contents over the rooting depth (0–120 cm). Model efficiency was also satisfactory for other variables. It ranged between 0.73 and 0.80 for grain N concentration, crop N uptake and legumes N_2 fixation, and was 0.90 and 0.63 when simulating crops aerial biomass and grain yield, respectively (Plaza-Bonilla et al., 2015). Moreover, statistical criteria, such as r^2 , model efficiency, relative root mean square error and mean difference, corresponding to the comparison between cumulative observed and simulated N_2O emissions of a subsequent version of this experiment were also found correct, with values of 0.40, 0.24, 45.6% and $0.1 \text{ kg N}_2O\text{--}N \text{ ha}^{-1}$, respectively (Plaza-Bonilla et al., 2017a).

The soil and crop model STICS (Brisson et al., 1998, 2002, 2008) is a one-dimension daily-step model. It uses pedoclimatic and crop characteristics, and management practices as inputs for the simulation of growing seasons resulting on different crop and soil outputs. Climatic inputs were obtained on the site ($< 100 \text{ m}$ far) at a daily scale. In the model, soil was divided in five different layers (i.e. 0–15, 15–30, 30–60, 60–90, 90–120 cm) of given key characteristics. Different parameters such as crop species, phenology, leaf area index (LAI) and sensibility to stresses like drought are the crop parameters needed by the model. Finally, some information related to crop management practices (e.g. date, amount of input, soil depth) is required as a model input. Management practices information was available in the database of the experiment. Soil N_2O emissions as a result of nitrification and denitrification processes are simulated separately in the model and coupled by nitrate production by nitrification. In the model nitrification is

proportional to soil ammonium content. This process is modulated by water filled pore space (WFPS), soil temperature and pH. However, soil pH values in the experiment, ranging between 6.6 and 8.2, do not constrain nitrification. Denitrification is proportional to soil nitrate concentration and soil denitrification potential rate, which is modulated by soil pH and WFPS. The rate was checked from field samples and was found equivalent to $2 \text{ kg N}_2\text{O-N ha}^{-1} \text{ d}^{-1}$ (Plaza-Bonilla et al., 2017a). Ammonia volatilization is proportional to N fertilizer rate and depends on crop N uptake rate and soil pH. The model was parameterized and evaluated for crop growth and water and mineral N dynamics to estimate nitrate leaching (Plaza-Bonilla et al., 2015) and for direct soil N_2O emissions and ancillary variables (Plaza-Bonilla et al., 2017a) under the conditions of the field experiment. Simulated nitrate leaching and ammonia volatilization were transformed to indirect N_2O emissions taking into account the EF reported by the IPCC, i.e. 0.75% and 1%, respectively (IPCC, 2006). Afterwards, N_2O was transformed to Ceq taking into account a global warming potential of 265 (IPCC, 2013). Finally, CO_2 emissions resulting from urea hydrolysis were calculated using an EF of $0.2 \text{ kg CO}_2\text{-C kg}^{-1} \text{ urea}$ (IPCC, 2006).

The change in the stock of soil organic carbon (SOC) at the plow layer (0–30 cm depth) was quantified by analyzing SOC concentration and soil bulk density at the beginning of the experiment (2003) and after one (2006) and two (2009) complete rotation cycles. Organic C concentration was determined with a Leco-2000 analyzer (LECO, St. Joseph, MI, US).

SOC stocks annual change was quantified as the slope of the linear relationship between SOC and the year of sampling using a mixed linear model with random effect to account for differences between replicates on the intercept while the slope was considered to be equal for the different replications (i.e. fixed effect) (Plaza-Bonilla et al., 2016). This analysis helped to consider possible differences in initial soil organic C values between plots. That value was considered to be the representative of the annual change for the duration considered here.

The different items were calculated as six year average of two successive three-year rotations for each cropping system. When not explicitly described in the text, data are reported as $\text{kg CO}_2 \text{ eq. ha}^{-1} \text{ yr}^{-1}$. Finally, for each cropping system, the carbon footprint was divided by the amount of grain C and grain N produced to obtain an indicator relating the environmental and agronomic dimensions. Analyses of variance were performed using the JMP 13 Pro statistical package (SAS Institute Inc, 2017) for a completely randomized design with blocks with cropping system and year and their interaction as fixed effects and block as random effect.

3. Results

3.1. Environmental conditions and cropping systems productivity

Precipitation differed greatly among the six cropping seasons studied, with values below the 30-yr average (685 mm) in the first four seasons (Fig. 2). Differently, the 2008–2009 season was characterized by a wetter autumn than the average and high precipitation values in April 2009. Mean annual temperature was close to the 30-yr average, 13.7°C , with values ranging between 13.3 and 14.2°C .

Durum wheat grain yield presented a quite narrow range from 4974 to 5458 kg ha^{-1} , without significant differences between cropping systems in the period studied (2005–2010) ($P = .07$) (Table 5) due to a large soil water content at field capacity which allowed buffering precipitation water deficit at late development stages. Similarly, the incorporation of cover crops in the rotations did not affect significantly the grain yield of the other cash crops studied (with P values of 0.33, 0.51, 0.71, 0.66 and 0.75 for sorghum, sunflower, winter and spring pea and soybean, respectively) (Table 5).

3.2. External emissions

Greater annual external emissions were quantified for the cropping systems without grain legumes compared to GL1 and GL2, reaching values of 1362 and $1358 \text{ kg CO}_2\text{eq ha}^{-1} \text{ yr}^{-1}$ in GL0-BF and GL0-CC, respectively (Fig. 3). External emissions related to fertilizers represented between 47 and 62% of the entire C footprint excluding SOC changes (Table S1). The adaptation of crop N fertilization in each cropping system had a great impact on external emissions. GL1-BF and GL2-BF lowered by 50% and 102% the external emissions related to N fertilizers, respectively, compared to GL0-BF. The reduction was smaller in the systems with cover crops, attaining a reduction of 40% and 70% in GL1-CC and GL2-CC compared to GL0-CC, respectively. Emissions related to N fertilizers accounted for 90% of external emissions in GL0-BF, GL0-CC, GL1-BF, and GL1-CC, while that value was reduced by 80% in GL2-BF and GL2-CC. Differently, the proportion of emissions due to energy consumption for irrigation was higher for GL2-BF and GL2-CC systems reaching 12% of the external emissions, while ranged between 0 and 6% for the rest of treatments. The emissions related to seeds and pesticides only represented 5% and 1% of the external emissions, respectively, as an average of the different cropping systems compared. Durum wheat seeds represented the greatest emissions when compared with the rest of cash crops, due to the amount of input used (i.e. sowing rate) and N fertilizer requirements to produce this crop. In the cropping systems with cover crops, the use of vetch and vetch-oat mixtures particularly increased the indirect emissions related to seeds given their higher sowing rate compared to mustard. However, energy consumption for irrigation, and indirect emissions related to seeds and pesticides had a low contribution on the C footprint excluding SOC, representing a 4, 3 and 1%, respectively, as an average of the six cropping systems compared (Table S1).

3.3. On-site emissions

3.3.1. Machinery emissions and volatilized CO_2 from urea hydrolysis

As an average of crop sequences and years, machinery emissions were similar between crop rotations without cover crops being the values 232, 250 and $245 \text{ kg CO}_2 \text{ eq. ha}^{-1} \text{ yr}^{-1}$ in the GL0-BF, GL1-BF and GL2-BF cropping systems, respectively (Fig. 4). The increase in the use of machinery for the establishment, chopping and incorporation by soil tillage of cover crops led to greater machinery emissions in GL0-CC, GL1-CC and GL2-CC, with values of 288, 337 and $317 \text{ kg CO}_2 \text{ eq. ha}^{-1} \text{ yr}^{-1}$, respectively (Fig. 4). In average of cropping systems, machinery use represented between 11 and 23% of the C footprint excluding SOC changes (Table S1).

Carbon dioxide emission as a byproduct of urea hydrolysis was only accounted for sunflower and sorghum fertilization in GL0-BF and GL0-CC cropping systems and in 2009 for sunflower in GL2-BF and GL2-CC (Table 2). The resulting mean emissions of this process were $67 \text{ kg CO}_2 \text{ eq. ha}^{-1} \text{ yr}^{-1}$ for the cropping systems without legumes and $3.0 \text{ kg CO}_2 \text{ eq. ha}^{-1} \text{ yr}^{-1}$ for the cropping systems with one grain legume (Fig. 4), being a 3% of the C footprint excluding SOC changes (Table S1).

3.3.2. Simulation of soil N_2O direct emissions and N_2O indirect emissions

As an average of the three crop sequences, simulated cumulative soil N_2O emissions during the six years (from 2005 to 2010) were 4.8, 2.9 and $3.8 \text{ kg N}_2\text{O-N ha}^{-1}$ for the GL0-BF, GL1-BF and GL2-BF. In the case of the counterparts with cover crops, the values were 3.7, 4.2 and $3.9 \text{ kg N}_2\text{O-N ha}^{-1}$ for GL0-CC, GL1-CC and GL2-CC, respectively. In average of the six cropping systems, direct soil N_2O emissions would represent between 13 and 20% of the C footprint excluding SOC changes. According to the STICS model simulations, soil N_2O emissions were highly dynamic and dependent of the combination between the crop and the cropping seasons (Fig. 5). Peaks of greatest magnitude were simulated mainly after N application to summer non-legume crops (mainly sorghum and, with less importance, sunflower) in the most N-

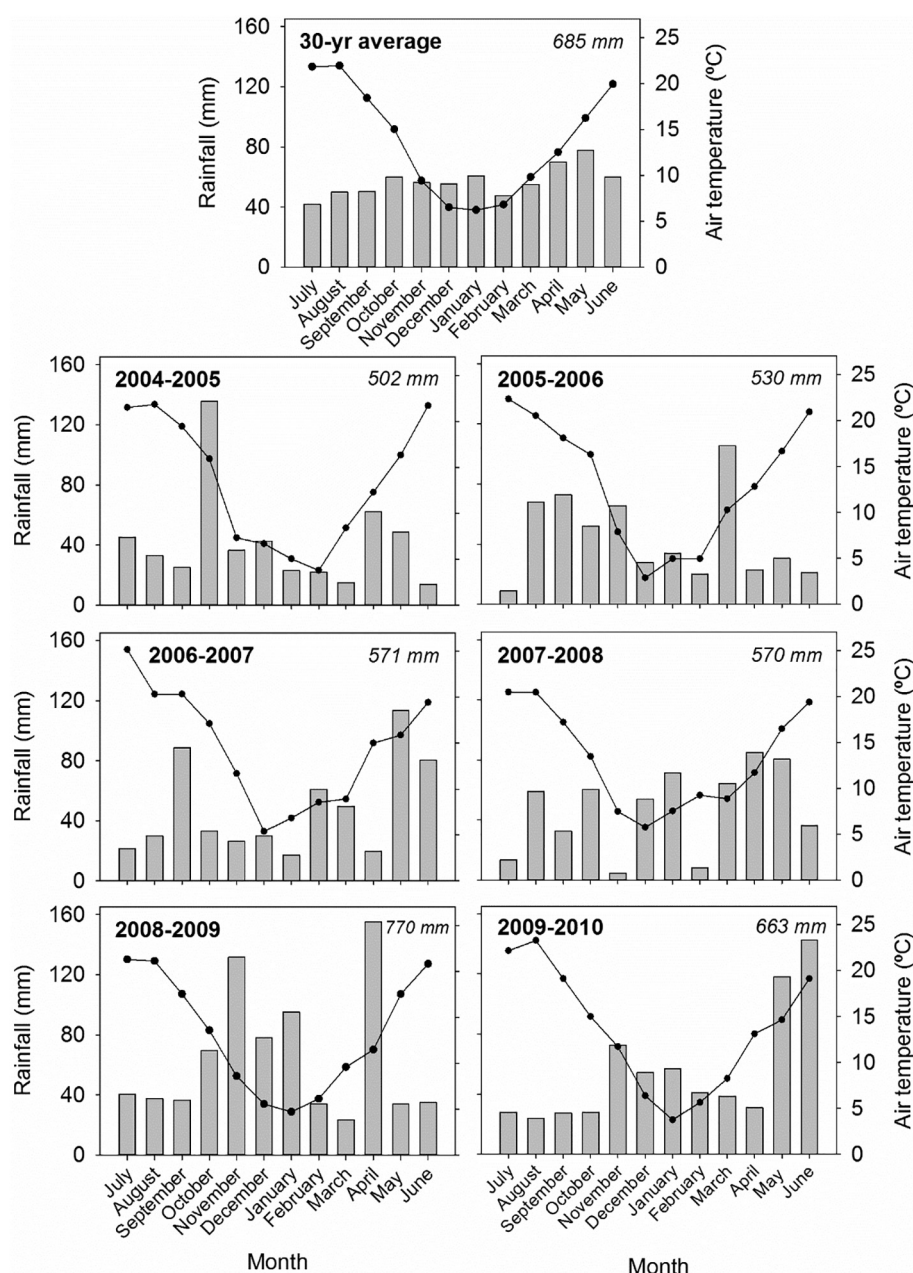


Fig. 2. Monthly precipitation (grey bars) and air temperature (solid black line) at the experimental site: 30-yr (1981–2010) average values and 2004–2005, 2005–2006, 2006–2007, 2007–2008, 2008–2009 and 2009–2010 cropping seasons. Cropping season precipitation is shown in italics.

dependent cropping systems (i.e. GL0-BF and GL0-CC) (Fig. 5a–c). Moreover, in some cases, the incorporation of low C:N ratio biomass from cover crops increased simulated soil N_2O emissions, such as the case of vetch-oat mixture in GL1-CC (Fig. 5d). Except for durum wheat, the rest of crops present in GL2-BF and GL2-CC, the least N-dependent systems, led to small magnitude soil N_2O peaks, although the basal emission of this gas from the soil did not decreased the cumulative values (Fig. 5g–i).

Simulated nitrate leaching in the different cropping systems compared was reported in a previous publication (Plaza-Bonilla et al., 2015). During the six years analyzed the amount of N lost as leaching was estimated to be 22.3, 32.0 and 52.2 kg N ha⁻¹ in GL0-BF, GL1-BF and GL2-BF, respectively, while the values were reduced to 15.7, 20.5 and 18.0 kg N ha⁻¹ in GL0-CC, GL1-CC and GL2-CC, respectively, as an average of the three possible crop sequences. These values represented the indirect emission of 11.6, 16.7 and 27.2 kg CO₂ eq. ha⁻¹ yr⁻¹ in the

GL0-BF, GL1-BF and GL2-BF treatments, respectively, and 8.2, 10.7 and 9.4 kg CO₂ eq. ha⁻¹ yr⁻¹ in GL0-CC, GL1-CC and GL2-CC, respectively. According to the simulations performed, during the six years analyzed ammonia volatilization from fertilizer-N amounted to 52.7, 12.1 and 12.6 kg NH₃-N ha⁻¹ in GL0-BF, GL1-BF and GL2-BF treatments, respectively, and to 60.3, 15.6 and 15.3 kg NH₃-N ha⁻¹ in GL0-CC, GL1-CC and GL2-CC treatments, respectively. These values represented the indirect emission of 36.6, 8.4 and 8.8 kg CO₂ eq. ha⁻¹ yr⁻¹ in the GL0-BF, GL1-BF and GL2-BF treatments, respectively, and 41.8, 10.8 and 10.6 kg CO₂ eq. ha⁻¹ yr⁻¹ in GL0-CC, GL1-CC and GL2-CC, respectively. The contribution of indirect emissions of N₂O from nitrate leaching and ammonia volatilization on the C footprint excluding SOC was low, representing less than a 2% of the total emissions.

3.3.3. Changes in soil organic carbon stocks

The annual change in the stock of soil organic carbon (SOC) at the

Table 5

Cash grain yield (dry matter) in the different cropping systems compared (GL0, GL1 and GL2, 3-year rotation with 0, 1 and 2 grain legumes, respectively; BF and CC, bare fallow and cover crops, respectively). Values correspond to the average of 6 years (i.e. 2005–2010 period). Values between brackets correspond to the standard deviation.

Rotation	Cash crop	Cover crop treatment	
		BF	CC
GL0	Sorghum	6613 (617)	6782 (709)
	Sunflower	2678 (455)	2506 (463)
	Durum wheat	4974 (799)	5012 (803)
GL1	Sunflower	2581 (599)	2693 (473)
	Winter pea	2645 (1316)	2705 (1027)
	Durum wheat	5458 (902)	5296 (666)
GL2	Soybean	3092 (635)	3005 (726)
	Spring pea	3260 (1123)	3322 (1127)
	Durum wheat	5282 (734)	4991 (1120)

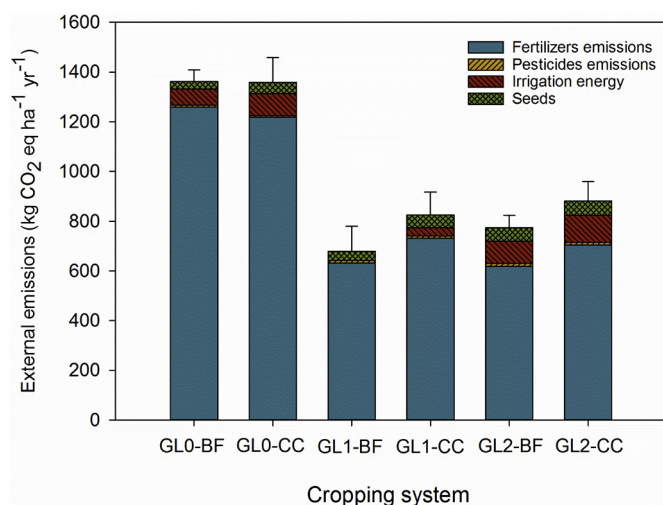


Fig. 3. External emissions related to fertilizer, pesticides and seeds production and transportation and to energy needed to pump irrigation water as affected by cropping system (GL0, GL1 and GL2, 0, 1 and 2 grain legumes in a 3-years rotation; CC, cover crop and BF, bare fallow). Values correspond to the annual average of the 2005–2010 period. Vertical bars correspond to the standard deviation. For color version of this figure, the reader is referred to the online version of this article.

plow layer (0–30 cm depth) was reported in a previous publication (Plaza-Bonilla et al., 2016). With the exception of the GL0-CC cropping system, which sequestered SOC at a rate of 284 kg C ha⁻¹ yr⁻¹, the rest of cropping systems significantly lost SOC. The loss was of a greater magnitude when grain legumes were included in the cropping system, although mitigated with the introduction of cover crops: –233, –595 and –735 kg C ha⁻¹ yr⁻¹ in GL0-BF, GL1-BF and GL2-BF, respectively, and –493 and –246 in GL1-CC and GL2-CC, respectively.

3.4. Cropping systems carbon footprint and its relation to grain C

The change in SOC stocks had a great and key impact on the C footprint of the different cropping systems (Table 6). Carbon footprint of the six cropping systems showed a high variation with values ranging between 977 and 4015 kg CO₂ eq ha⁻¹ yr⁻¹ (Table 6), being found these values in the GL0-CC and the GL2-BF treatments, respectively, when including SOC in the assessment. When no cover crops during the fallow period were cropped between main cash crops, the increase in the number of grain legumes in the 3-yr rotations led to a significant increase in the C footprint. Thanks to a longer photosynthetic activity at the rotation scale and then a greater CO₂ capture, the introduction of

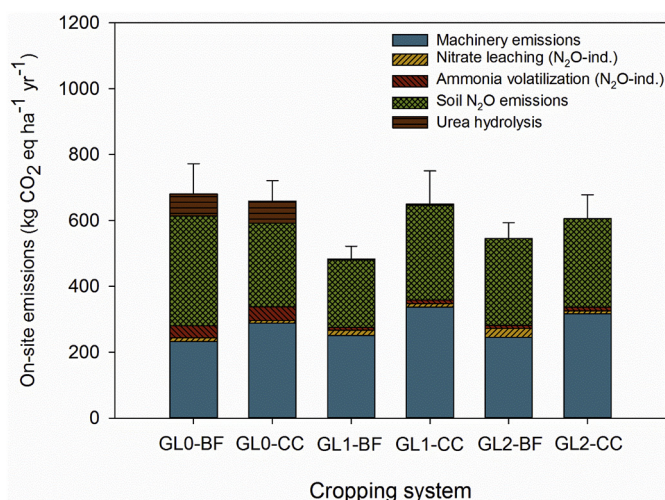


Fig. 4. On-site emissions related to machinery use, N₂O indirect emissions as nitrate leaching and ammonia volatilization, soil N₂O direct emissions, and CO₂ emissions due to urea hydrolysis as affected by cropping system (GL0, GL1 and GL2, 0, 1 and 2 grain legumes in a 3-years rotation; CC, cover crop and BF, bare fallow). Values correspond to the annual average of the 2005–2010 period. Vertical bars correspond to the standard deviation. For color version of this figure, the reader is referred to the online version of this article.

cover crops led to a significant decrease in the carbon footprint in the rotations without and with two grain legumes, compared with their counterparts without cover crops (Table 6). When SOC stocks were excluded from the quantification of C footprint the cropping systems without grain legumes (GL0-BF and GL0-CC) showed significantly greater values than the ones with grain legumes (Table 6). Moreover, in this case, the introduction of cover crops increased the C footprint in the cropping systems with one and two grain legumes (i.e. GL1-CC > GL1-BF and GL2-CC > GL2-BF). The differences found between cropping systems on the quotient between C footprint including SOC and the amount of grain C produced were in the line of the ones obtained in the C footprint (Table 6). Due to lower yields of grain legume than cereals, the cropping systems with one grain legume (GL1-BF and GL1-CC) and the one with two grain legumes without cover crops (GL2-BF) presented the highest C footprint per each kg of grain C produced, with values between 2100 and 2430 g CO₂ eq kg⁻¹ grain C. When grain N was used in the quotient, GL2-BF showed lower values than GL1-BF and GL1-CC, thanks to its greater protein production. Finally, SOC exclusion lowered the ratios between C footprint and grain C and N in the cropping systems with grain legumes. Therefore, the introduction of cover crops lowered the C footprint per each kg of grain C and per each kg of grain N produced in the rotations without and with two grain legumes.

4. Discussion

4.1. SOC changes as a key component for analyzing multi-year C footprint

The objective of this study was to analyze the impact of the diversification of cropping systems with grain legumes and cover crops on the C footprint up to the farm gate considering two entire 3-year rotation cycles. This duration allowed obtaining significant conclusions corresponding to the pedoclimatic zone, which presents inter-annual weather variability. Given the cropping system framework of analysis (Drinkwater, 2002), not only the crop sequence differed between treatments but also different crop management practices were adapted. The quantification of the C footprint up to the farm gate for different cropping systems encompasses important items of the ‘farming systems’ framework. Among other, (i) our study compares different orientation

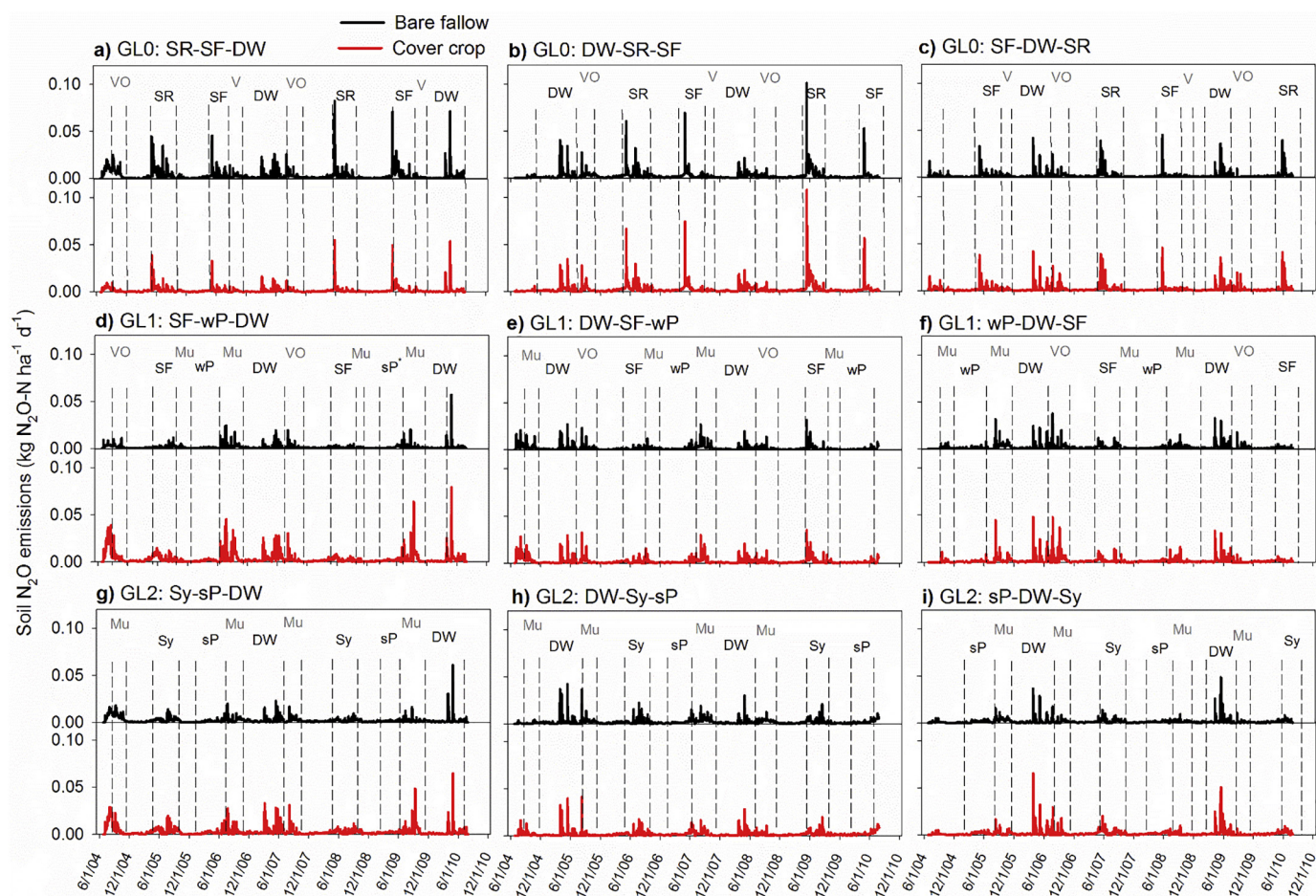


Fig. 5. Simulated soil N_2O emissions (2004–2010) as affected by crop rotation (GL0, GL1 and GL2, 3-yr rotations with 0, 1 and 2 grain legumes, respectively) and cover crop treatments. The three crop sequences of each rotation are shown horizontally as sub-figures (a, b and c: crop sequences of GL0; d, e and f, crop sequences of GL1; g, h and i, crop sequences of GL2). Dashed lines delineate the season covered by each cash (in black letters) and cover crop (in grey letters) and fallow periods. DW, Mu, SF, sP, SR, Sy, V, VO, wP stand for durum wheat, mustard, sunflower, spring pea, sorghum, soybean, vetch, vetch-oat mixture and winter pea, respectively. Note that each sub-figure shares X-axis. For color version of this figure, the reader is referred to the online version of this article.

of arable crop farms and (ii) uses C footprint as a holistic indicator, which integrates fieldwork (i.e. machinery use), crop productivity and several environmental impacts of cropping practices.

One of the main outcomes of this study is the great impact of SOC changes on the magnitude of C footprint of the different cropping systems analyzed. When SOC change was excluded from the quantification, C footprint was lower in the cropping systems including grain legumes compared to GL0. Similarly, Barton et al. (2014) observed a 56% reduction in GHG emissions from wheat production when incorporating a lupin (*Lupinus angustifolius* L.) crop in a 2-yr rotation.

However, our results indicated different trends when including the change in SOC in the analysis. Some studies pointed out a reduced SOC loss in legume-based cropping systems compared to cereal-based cropping systems (Drinkwater et al., 1998), mainly when legume leys are established, since they allocate more carbon below-ground and drastically reduce bare fallow periods (Freibauer et al., 2004). In the present study, greater losses of SOC were observed when introducing annual grain legumes in the 3-yr rotations without cover crops. Differently, the rotation without grain legumes and with cover crops (GL0-CC) showed an increase in SOC stocks after 6 years which reduced

Table 6

Carbon footprint, C footprint per kg of grain carbon, and C footprint per kg of grain nitrogen including and excluding soil organic carbon (SOC) changes as affected by cropping system (GL0, GL1 and GL2, 3-year rotation with 0, 1 and 2 grain legumes, respectively; BF and CC, bare fallow and cover crops, respectively). Values correspond to the annual average of the 2005–2010 period. Values between brackets correspond to the standard deviation. Different letters indicate differences between cropping systems at $P < .05$.

Cropping system	C footprint ($\text{kg CO}_2 \text{ eq ha}^{-1} \text{ yr}^{-1}$)		C footprint kg^{-1} grain C ($\text{g CO}_2 \text{ eq kg}^{-1}$ grain C)		C footprint kg^{-1} grain N ($\text{kg CO}_2 \text{ eq kg}^{-1}$ grain N)	
	Including SOC	Excluding SOC	Including SOC	Excluding SOC	Including SOC	Excluding SOC
GL0-BF	2897 (111) c	2043 (111) a	1423 (89) b	974 (67) a	32 (4) b	22 (3) a
GL0-CC	977 (101) e	2018 (102) a	411 (57) c	976 (77) a	9 (1) d	21 (2) a
GL1-BF	3344 (127) b	1162 (127) d	2430 (709) a	698 (140) b	41 (12) a	12 (3) bc
GL1-CC	3282 (142) b	1475 (142) b	2100 (252) a	824 (48) b	36 (5) ab	14 (1) b
GL2-BF	4015 (44) a	1320 (44) c	2458 (413) a	744 (103) b	31 (6) b	10 (2) c
GL2-CC	2389 (139) d	1487 (139) b	1429 (182) b	842 (122) ab	18 (3) c	11 (2) bc

significantly its C footprint. This result would be the consequence of the combination of (i) a greater amount of inputs of (ii) lower decomposability and (iii) the possible role played by N limitation in GL1 and GL2. In this line, as an average of the 6 years of experiment, carbon inputs were 2385 and 2978 kg C ha⁻¹ yr⁻¹ in the cropping systems without cover crops and with cover crops, respectively (Plaza-Bonilla et al., 2016). Increasing the amount of residue returned to the soil leads to greater SOC stocks (Huggins et al., 1998). In turn, C:N ratio of the crop residues was higher in the cropping systems without grain legumes (62 and 59 for GL0-BF and GL0-CC, respectively, compared to 47, 39, 50 and 41 for GL1-BF, GL1-CC, GL2-BF and GL2-CC, respectively) (Plaza-Bonilla et al., 2016). Moreover, grain legume crop residues have a lower lignin content, which can increase decomposition (Tian et al., 1992). The level of N fertilizer applied in each cropping system could also explain the greater SOC in GL0. Regarding to this, the “microbial nitrogen mining” hypothesis indicates a decrease in soil organic matter decomposition rates at higher nitrogen availability. Thus, in systems with lower availability of N, microorganisms would use labile C to decompose recalcitrant organic matter to acquire N (Craine et al., 2007). Moreover, it has been shown that the application of high levels of N reduces the mass loss of high-lignin materials (Fog, 1988; Knorr et al., 2005) such as sorghum residues, slowing down the overall decomposition process (Mary et al., 1996). In this line, Fog (1988) concluded that N negative effect is mainly found with recalcitrant organic matter of a high C:N ratio, while a positive effect (i.e. greater decomposition with N availability) is commonly found for easily degradable materials. Therefore, the higher N fertilizer rates applied in the GL0 cropping systems in combination with the presence of lignin compounds in sorghum could also partly explain the lower loss of SOC in GL0-BF and SOC increase in GL0-CC compared to the rest of cropping systems.

Depending on their management, agricultural soils can act as a source or sink of CO₂ (i.e. soil carbon sequestration), which is also well illustrated by our results. The impact of agricultural practices on SOC will then increase or offset the CO₂ eq emitted because of crop production activities. In this line, our results highlight the need to take into account SOC changes in carbon footprint analysis in agricultural systems. This aspect agrees with the findings of Yang et al. (2014) who observed a significant increase in SOC sequestration (0–20 cm depth) in five diversified crop rotations in the North China Plain, which modified the C footprint of the cropping systems. Similarly, Gan et al. (2012) highlighted the significant influence of long-term (25 years) soil carbon change on the value of C footprint for spring wheat when comparing different fallow frequencies in Saskatchewan, Canada. The last authors reported a reversion of the carbon footprint values from positive to negative (i.e. soils acting as a net sink of CO₂ counteracting the CO₂ eq emitted by the rest of components within the C footprint thresholds) when including SOC changes in the calculation, as also stressed by Knudsen et al. (2014). However, it must be taken into account that SOC levels could reach an apparent equilibrium after any change in the cropping system (management practices and/or crop rotation) (West and Six, 2007). The timeframe needed to reach this equilibrium will depend on soil management, historical land-use and pedoclimatic conditions (West et al., 2004). Then, although our data indicates a great impact of grain legumes and cover crops on SOC in the short-term, this process would have a lower impact when reaching the new steady state. Differently, other items of the C footprint such as direct and indirect GHG emissions from N fertilizers would be permanently affected by the adoption of this novel cropping systems. Therefore, fostering grain legumes would reduce the C footprint in the long-term.

4.2. Grain legumes and cover crop incorporation in the cropping systems: impacts on C footprint

The introduction of grain legumes in the crop rotations without cover crops (GL1-BF and GL2-BF) led to a greater C footprint, which

was not necessarily expected. Nevertheless, Jensen et al. (2012) suggested a potential SOC sequestration when including grain legumes in cropping systems, provided reduced tillage or no-tillage techniques are used. Therefore, one possible strategy to reduce the negative impact of SOC losses on C footprint in the cropping systems with legumes tested could be the adoption of reduced tillage or no-tillage practices that should be compatible to low input systems in order to avoid a greater use of pesticides.

The introduction of grain legumes led to a significant decrease in the external emissions related to fertilizers, mainly due to the lower requirements of N (as ammonium nitrate and urea) associated to the biological nitrogen fixation of the grain legumes. The manufacturing of nitrogen fertilizer is a highly energy-consuming process, which relies on high temperatures and pressures to synthesize NH₃, resulting in a significant amount of CO₂ emitted to the atmosphere (Nemecek and Erzinger, 2005). Moreover, the use of a lower amount of urea fertilizer to sunflower in GL1 also led to a reduction in the amount of CO₂ volatilized from urea hydrolysis. The complete reliance of the cropping system without legumes (GL0-BF) on N fertilizer also led to greater on-site emissions as direct soil N₂O emissions, as simulated with the STICS model. According to the model, these emissions would be greatest during N fertilizer applications and, in specific cases, when incorporating low C:N ratio biomass from legume cover crops, which agrees with the existing literature (Bouwman et al., 2013; Rochette and Janzen, 2005). The magnitudes simulated with the model are in agreement with the values reported by Peyrard et al. (2016) and Plaza-Bonilla et al. (2017a), who measured and simulated the emission of N₂O on a novel version of this cropping system experiment also including legumes, such as faba bean and cover crop mixtures. Nitrous oxide is a powerful greenhouse gas, resulting from a range of biological N transformation processes, being the nitrification and denitrification of a great importance (Butterbach-Bahl et al., 2013). The introduction of legumes in crop rotations has been long discussed as a key strategy to reduce the direct emissions of N₂O from soils, due to the reduction of N fertilizer needs (Jensen et al., 2012). Improving N use efficiency in arable cropping systems is key to improve their environmental performance (Prechsl et al., 2017).

The introduction of cover crops in the cropping systems was crucial to reduce the C footprint. The use of cover crops in cropping systems is a promising strategy to sequester carbon in soils, among other benefits, since the period of photosynthesis is lengthened at the rotation scale. In this line, in a meta-analysis, Poeplau and Don (2015) reported an annual SOC sequestration rate of 0.32 Mg ha⁻¹ when using cover crops. However, according to the results, the introduction of cover crops slightly increased the external emissions related to fertilizers. In our experiment, the N fertilizer rate was slightly increased in the cropping systems with cover crops according to the results of the balance-sheet methodology used to define N fertilization (Plaza-Bonilla et al., 2017b). Cover crop management was optimized with an early date of incorporation in November (Table 5). This early date was determined to avoid preemptive competition for water and N and have a good synchrony of N release from the decomposition of cover crops residues with the needs of the subsequent cash crop. Preemptive competition stands for the reduction of the mineral N caused by cover crop use, reducing the amount of N available for the succeeding crop. This process mainly occurs in seasons with low or no water drainage and concomitant low or no nitrate leaching (Thorup-Kristensen and Nielsen, 1998), as occurred in the experimental area in the first four cropping seasons, therefore, N fertilization needs to be adapted.

The cropping systems with cover crops also presented greater on-site emissions related to the machinery use for their establishment and termination (i.e. pre-sowing soil tillage, sowing and cover crops incorporation to the soil). Similarly, Prechsl et al., (2017) reported slightly higher global warming potential due to the energy demand in cropping systems with cover crops compared to the use of fallow between cash crops in a cropping systems experiment in Switzerland.

These emissions did not counteract the lower C footprint in these cropping systems, which was the result of the positive incidence of cover crops on the mitigation of SOC losses. However, the energy needs and concomitant costs resulting from cover crops use can suppose a hindrance for the implementation of this strategy by farmers (Gabriel et al., 2013).

5. Conclusions

The results of this study highlighted the importance of including soil organic carbon changes for doing a relevant analysis in C footprint assessments of arable cropping systems. Grain legumes introduction into low input crop rotations led to SOC losses, counteracting the positive impact of legumes in the reduction in external and on-site emissions related to N fertilizers. Therefore, our results support the need to include SOC changes in environmental assessments of agricultural production. However, according to the literature, SOC changes are finite in time if the different factors regulating the soil C balance (e.g. crop management practices, crop sequence, climatic conditions) remain unchanged. Therefore, the timeframe of environmental assessments of cropping systems must be clearly identified. Cover crops introduction in the cropping systems analyzed was key to reduce the C footprint, due their positive impact on SOC loss mitigation, indicating their potential as a CO₂ offsetting strategy in agricultural production. However, cover crops need to be carefully implemented by farmers given the economic costs associated to management practices (i.e. establishment and termination). It can then be recommended to policy makers that the use of cover crops must be explicitly taken into account and thus remunerated at their fair value. More research is needed to design grain legume-based cropping systems which allow maintaining SOC levels in low-input agricultural systems to improve the C footprint.

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Appendix A. Supplementary data

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